A 750keV LINAC INJECTOR UPGRADE PROPOSAL

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Table of Contents

Abstract

The present FNAL Linac H- injector has been operational since 1978 and consists of a magnetron H- source and a 750keV Cockcroft-Walton Accelerator. The proposed upgrade to this injector is to replace the present magnetron and Cockcroft-Walton with a new magnetron and 200MHz RFQ. Operational experience gained at other laboratories has shown that a similar upgraded source and RFQ design will be more reliable and require less manpower than the present system.

1. Introduction

The present FNAL injector has been operational since 1978 and has been a reliable source of H- beams for the Fermilab program. At present there are two Cockcroft-Walton pre-injectors, each with a magnetron H- source [1]. Normally one source and Cockcroft-Walton is operational at any one time, with the other on stand by and ready to take over if there is a failure. With this operation the combined injector has a reliability of better than 97%. However, issues with maintenance, equipment obsolescence, and retirement of critical personnel, have become difficult obstacles for the continued reliable running of the H- injector. The recent past has seen an increase in both downtime and source output issues. With these problems looming on the horizon, a new 750 keV injector has been proposed to replace the present system. The proposed system will be very similar to the one at BNL (Brookhaven National Laboratory) which has a similar magnetron source and a 200MHz RFQ. This combination has been shown to be extremely reliable operationally [2].

2. The Proposal

Based upon the experience at BNL and research/testing done at FNAL (HINS and source upgrade design studies) this paper proposes a round (dimpled) magnetron 35 keV source followed by a 750 keV RFQ. The design uses conventional technology such as solenoids, buncher cavity and steering elements to match into the present side coupled accelerating cavity. For a small additional cost adding a second magnetron, solenoid and steering elements is also being proposed to allow for uninterrupted maintenance and repair. The design is intended to reuse as much of the present power sources, beam line hardware and infrastructure in order to keep cost at a minimum. The only new items required are a small buncher cavity, two solenoids and a 1.5 m long RFQ and RF amplifier (beam pipe and the associated hardware will require mechanical labor.) This design which uses two magnetrons joined in a Y configuration followed by a chopper, RFQ, buncher (diagnostics and miscellaneous hardware) is similar to the SNS LEBT upgrade which is required to provide 99.5% [1] source availability [3]. The following paper will first describe our present injector and its operations and cost followed by the design section which will describe in detail the proposed design, physics and cost of the upgrade. For a comparison, an appendix is also included which looks at the BNL injector system.

3. Analysis of Present Operations

Dan's write up.

3.1. Level 2

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1   It can inferred from this statement that each SNS H- source is available 93% of the time.

3.1.1. Level 3

Your main text

3.1.1.a. Level 4

4. The Design

The design can be divided into two transport lines: the low energy beam transport (LEBT) and the medium energy beam transport (MEBT). The LEBT is the transport line before the RFQ and the MEBT is the transport line from the end of the RFQ to the beginning of the DTL.

For the LEBT, the proposed design will contain two H- magnetron sources for increased reliability. Each H- magnetron source will be the round type and will be mounted on a Y joint. (See Figure 4.1) The beam right out of the source is at 35 keV and should be > 60 mA and so is space charge dominated. Therefore, it must be focused with a solenoid right out of the source to preserve its emittance. The beam is bent by $15°$ with a dipole and two quadrupoles before and after the dipole are used to keep the beam focused when going through this bend. Once the beam makes it pass the bend, it is steered towards the entrance of the RFQ. One more solenoid is needed to strongly focus the beam into the small aperture (~1 cm in diameter) at the entrance of the RFQ. Xe gas will also be used for neutralizing and focusing the H- beam because it has been shown at BNL that there is an increased transmission efficiency when Xe gas is used [4]. A low energy chopper will be installed before the RFQ because it is much easier to kick the beam at low energy and there is insufficient space in the MEBT. It is necessary that the chopper be a magnetic kicker (or a combination of electrostatic-magnetic kicker) because a pure electrostatic kicker will de-neutralize the H- and so any advantage of Xe gas focusing will be lost during the chopping process [5].

The RFQ will focus, bunch and accelerate the H- beam from 35 keV to 750 keV. Once the beam exits the RFQ it has a tendency to blow up both longitudinally and transversely and so the MEBT must be short and must contain quadrupoles and a buncher. The proposed MEBT is a copy of the BNL MEBT which is < 75 cm long and contains 3 quadrupoles and one two gap buncher.

Using both empirical data and computer simulations, it is predicted that about 65% of the beam can be transported from the H- source to the end of the DTL 1. If the source can produce 60 mA of H- beam (Note: the BNL source routinely produces 90 – 100 mA of H- beam [2]), it is predicted that 37.5 mA will be at the end of the DTL 1. For a comparison, the present Cockcroft-Walton system transports 37.5mA to the end of the DTL 1 for a source current of ??. See Figure 5.1.

4.1. The H- Source

FNAL has been using an H- magnetron ion source for ~34 years and as such has

accumulated much experience and associated equipment associated with this source. Following the initial FNAL use, ANL (Argonne National Laboratory), DESY and BNL have also adopted this source design to produce H- beams for injection into their linacs. Originally, the source had a slit aperture producing a ribbon shaped beam which was transformed to an elliptically shaped beam which could be further accelerated, transported and injected into a linear accelerator. BNL improved it using a circular aperture to produce a round beam which could be more easily focused and injected into an RFQ. Recently, a source, very similar to the BNL source, was built and tested at FNAL for the HINS R&D program.

The recent work to produce a circular-aperture direct-extraction H- source for the HINS project is conveniently applicable to a source for this proposal. Likewise, two sources which was recently received from Argonne due to the dismantlement of the Intense Pulsed Neutron Source (one was loaned to them many years ago and the second ANL built as a spare) has given many significant parts for assembling the sources needed for this proposal. This will greatly reduce the effort, cost and time to have a working source for the RFQ tests and operation.

Like most accelerator equipment the H- source is operated at or near its maximum output and thus has a variable and limited lifetime (a good life time is about 3 to 4 months) so that it requires much maintenance and cleaning with frequent tuning during operation. To have high reliability from such an injector, it is very desirable to have two sources, one operating and one as backup, feeding the next device.

With the experience this source has had at FNAL and elsewhere it has become a logical choice to consider it for this proposal. The low duty-factor (0.2%), modest intensity (50 to ~100 mA), pulsed (15 Hz) H- ion source of the magnetron surface-plasma type is suitably matched to the capabilities of the present linac and Booster to meet the objectives of the FNAL program. It is not in the same league with the high current and high duty-factor modern H- sources which are used to produce intense secondary beams. Still, with proper attention and the manpower to maintain it, the magnetron source has and can continue to meet the capacity of the linac and Booster.

4.2. Optics for the LEBT

The H- beam from the source is space charge limited and at low energy its emittance will blowup if there is insufficient focusing. The combination of gas focusing and solenoid focusing will enable the transport of the H- beam with smaller losses to the entrance of the RFQ than without gas focusing. Care must be used with gas focusing because if the gas pressure is too high or the transport length is too long, stripping of the H- ions will become a problem. Furthermore, if an electro chopper is used for low energy chopping, the Xe ions used in gas focusing will be swept away by the electric field if it is turned on for too long. The solution to this problem is to either use a magnetic chopper or a combination electric-magnetic chopper. The chopper operation and design will be discussed in subsection **Error! Reference source not found.** Do we need to have a + potential barrier in the line?

4.2.1.   Focusing with Xe gas

The idea behind gas focusing is completely described by Reiser [6]. When low pressure Xe is introduced, one or both electrons can be stripped from the H- ion to form either H0 or H+ ions,

and Xe can form Xe+ ions and electrons. The electrons are repelled by the H- beam to the wall while the H+, Xe+ ions are trapped in the H- beam region. The H+, Xe+ ions attracts and focuses the H- beam as well as neutralize the H- beam. The gas that is used is Xe because its high atomic mass (131.3 amu) keeps the escape velocity of the Xe+ ions low and so keeps the Xe+ ions trapped.

A crude calculation which assumes that when the H- is over-neutralized, the amount of focusing of H- from the Xe+ ions, independent of beam current, is (Eq. 4.308 of Reiser [6])

$$a = 1.74 \times 10^5 \, \epsilon_n \frac{1}{\left[V_b V_i \right]^{1/4}} \tag{1}$$

where $\epsilon_n = \left[0.15 \times 10^{-5} \right] \text{m} \cdot \text{rad}$ or $1.5 \, \pi \, \text{mm} \cdot \text{mrad}$ (using $5\times$ rms emittance, see Table 4.2) is approximately the output emittance of the H- source, $V_b = 35 \, \text{kV}$ is the potential difference applied to the H- beam, $V_i = 12.1 \, \text{V}$ is the ionization potential of Xe when the H- beam goes through Xe gas and a is the radius of the focused beam. Putting in these numbers, the radius of the focused H-beam is $a = 3.2 \, \text{cm}$ and thus imply that the beam pipe must be at least 2.5" in diameter.

In fact, the BNL has demonstrated that by using low pressure Xe gas at $3.7 \times 10^{-6} \text{torr}$, the transmission efficiency of H- from the source to the entrance of the RFQ is improved by 30% over optics without the Xe gas [4]. Therefore, it is important to use Xe gas in the FNAL LEBT. However, since Xe does strip some H- to produce focusing, some intensity will be lost. The following is a simple formula which relates the fractional loss per unit length λ of H- to the molecular density $\rho \, [\text{m}^{-3}]$ of Xe in the beam pipe and ionization cross section $\sigma \, [\text{m}^2]$ of Xe:

$$\lambda = \rho \sigma \tag{2}$$

and so for the proposed LEBT, $\rho = \left[3.3 \times 10^{22} \right] \times \left[3.7 \times 10^{-6} [\text{torr}] \right] = 1.2 \times 10^{17} \text{m}^{-3}$ at 20°C[7] and $\sigma = 3 \times 10^{-19} \text{m}^2$ for 35 keV H- ions impacting on Xe [8], the fractional number of H- lost per metre is $\lambda = 0.036$. The LEBT is about 2 m long and so about 7% of the H- will be lost from gas stripping. Note: BNL measured 32% of H- loss from Xe gas stripping (and 20% loss by using Eq. (2)) for their 4m long LEBT [4]. Therefore, it can be expected that gas stripping for a 2 m long LEBT can be as high as 16%, i.e. a factor of two larger than the back of the envelope calculation shown above.

Another consideration is that it takes a finite time for neutralization to take place. BNL has measured it to be about $40 \mu s$ and so the pulse length must be increased by this amount, i.e. if the pulse length is $120 \mu s$, then only the last $80 \mu s$ is usable. LEBT optics with 2 H- sources
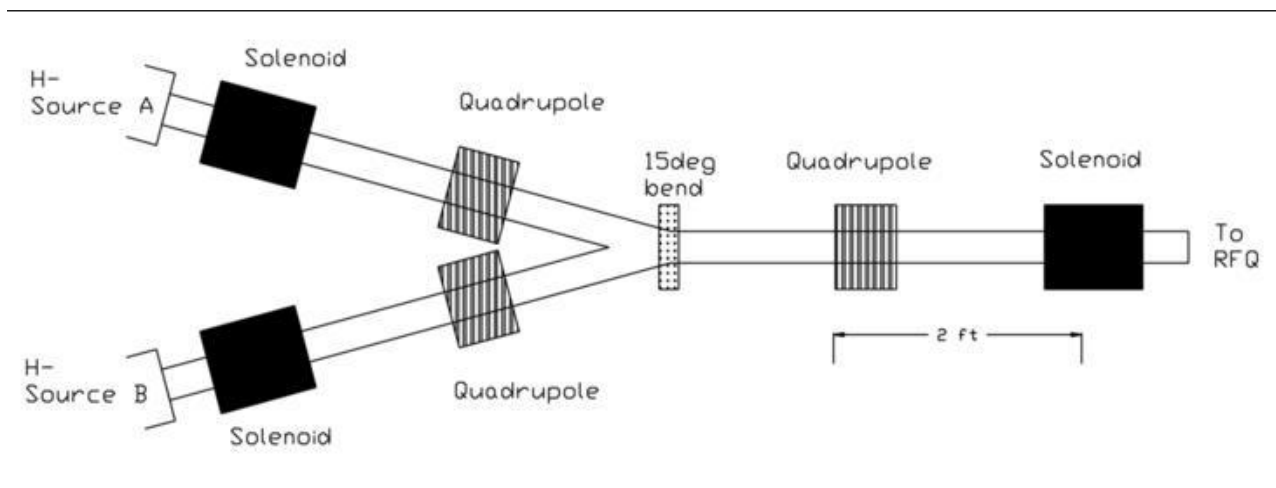
Figure 1*: The LEBT (drawn to scale) has 2 H- sources but only one is used at any given time. A Y joint with a dipole is used to bend the beam by 15˚ from either leg to the entrance of the RFQ. The zoomed in view of the Y joint is shown in Figure 4.2.*

The LEBT has been designed with two H- sources to ensure high reliability. Figure 4.1 shows a possible layout of the LEBT. A 30˚ angle has been chosen between the arms containing source A and source B so that 8" quads can be accommodated. Figure 4.2 shows a zoomed in view of the Y joint with the two quads. The 15˚ bend magnet will probably take up more space than shown in Figure 4.1, however there is plenty of space for it. Looking at the figures, although not shown, it is clear that there should be sufficient space for a chopper, instrumentation, beam stops and gate valves.

A simulation with Trace2D shows that the proposed layout can transport the beam from the source to the entrance of the RFQ. However, without Xe gas focusing, there will be scraping at the 15˚ bend because the beam does not fit in a 3" beam pipe. See Figure 4.3. With Xe gas focusing, it is expected that the beam will fit in the beam pipe (see section **Error! Reference source not found.**), but a better simulation will need to be done to demonstrate that this is indeed the case.

BNL's LEBT also has an Einzel lens which helps with the transport of the H- beam to the start of the RFQ. The Einzel lens improves transport from the H- source to the entrance of the RFQ by about 10% [4]. Again Trace2D does not have Einzel lens elements and so a better simulation will be needed to optimize its placement in the LEBT.
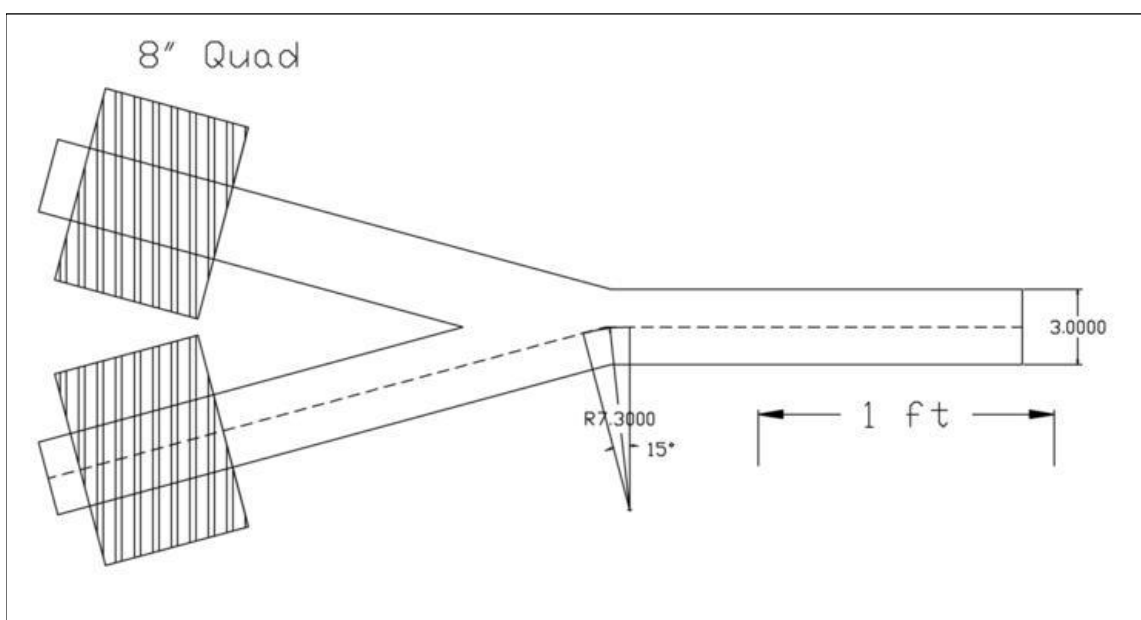
Figure 2: *This is the zoomed in view of the Y joint which connects the two branches together (drawn to scale). The beam is bent 15° before the RFQ.*

Trace2D Element ID	Element Type	Value	Comments
2	Solenoid	2333.6 G	BNL type solenoid.
4	Quad	0.18 T/m	3" aperture quad.
7	Bend	0.15 T	Radius of curvature 7.3", 15° bend.
10	Quad	0.16 T/m	3" aperture quad.
12	Solenoid	2335.7 G	BNL type solenoid.

Table 1 *Summary of the relevant parameters used to match the DC H- ion beam from the source to the entrance of the RFQ. See Figure 4.3 for the Trace2D element ID.*
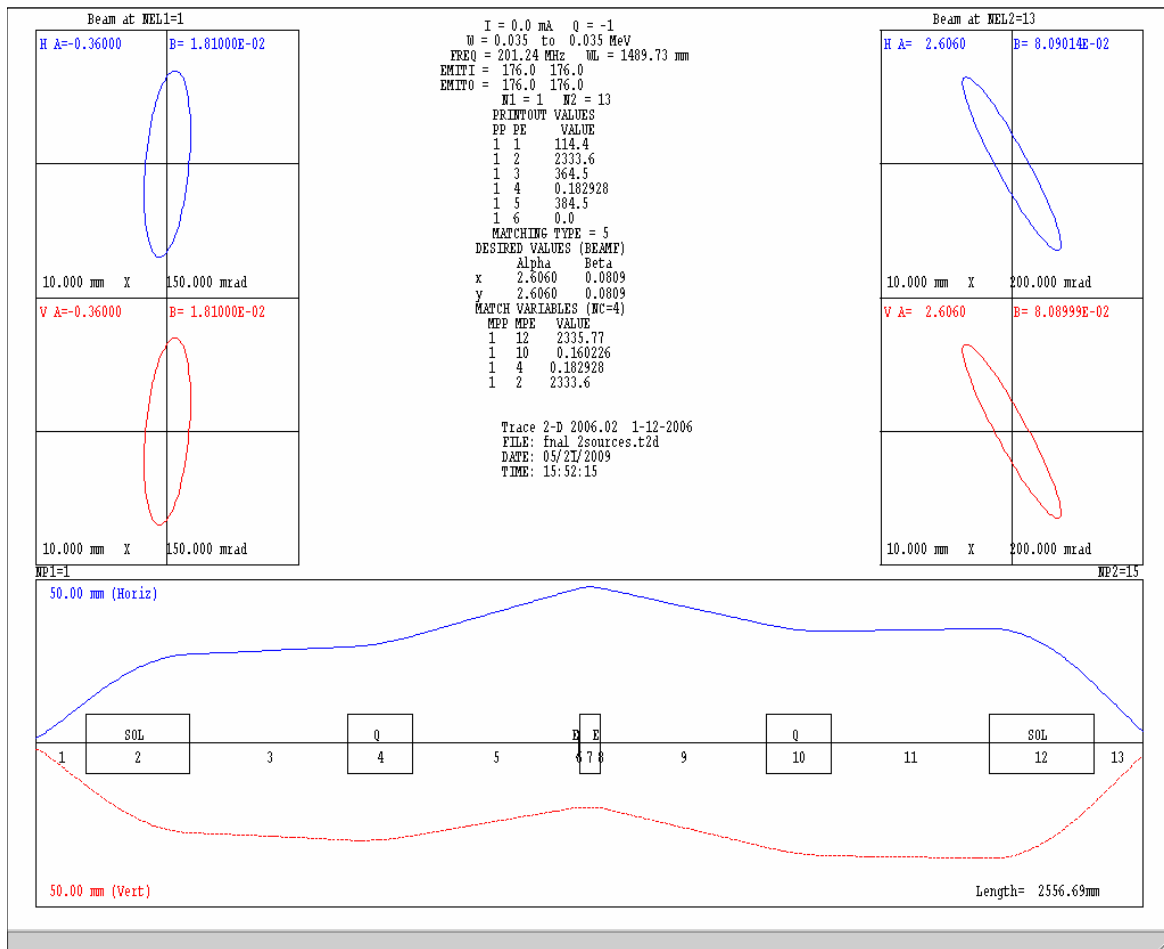
Figure 3: *The optics of the LEBT for zero current H- beam for one of the legs. In this simulation, the 15° bend magnet is assumed to have a non zero field index* $n = -\left[x/B_y\right]\left[dB_y/dx\right]$, *and in this calculation* $n = 10^{-6}$. *Note: bend is in the x-z plane and z is the direction of propagation.*

4.2.2.   Magnetic stripping of H-

B-fields can strip H- because the two electrons and the proton of the H- experience opposite Lorentz forces. The energy required to strip the loosely bound electron is only 0.75 eV, while in contrast it is 13.6 eV for the tightly bound one. However, for the magnetic fields and energy of the H- in the LEBT makes magnetic stripping irrelevant. A quick calculation below will show that this is indeed the case.

When the B-field in the laboratory frame is boosted to the frame of 35 keV H- ions, the H-ions will see an E-field $\vec{E} = \left[\gamma\right]\vec{v}/c \times \vec{B}$, which in more convenient units is

$$E[\text{MV/cm}] = 3.197 \, p[\text{GeV/c}] \, B[\text{T}] \tag{3}$$

where *p* is the momentum of the H- in the laboratory frame. The two sources of B-field in the LEBT are from the solenoids and from the 15° bend. The solenoidal field is about 0.2T and the bend

field is about 0.15T in the LEBT design. Therefore for 35 keV H- ions, the momentum is $p = 8.1$ MeV/c and so by using Eq. (3), the E-field for B=0.2T in the rest frame of the H- ion is $E = 5 \times 10^3 \, \text{V/cm} \ll 10^6 \, \text{V/cm}$ required for the weakly bound electron to tunnel through the potential barrier [9]. In fact, the present H- source has a $90°$ bend which has a B-field of 0.25T and there has been no noticeable H- loss. Therefore, the largest contributor to H- stripping is from gas stripping (see section **Error! Reference source not found.**) and not from magnetic stripping.

4.2.3.   Chopper

The chopper is in the LEBT and because it is at the low energy part of the injector, some care must be taken in the design and operation of the chopper because of previous experience at BNL. If electrostatic choppers are used and voltage is on the plates for a long period ($\gg 1 \, \mu s$), the H- emittance grows because the neutralizing Xe ions are swept out of the H- beam. In fact, from studies done at BNL, the neutralization is only lost in the region between the chopper plates [5].

In order to mitigate the "de-neutralization" of the H- described above, a simple electrostatic chopper is insufficient because even if the H- beam is transported to the RFQ when the voltage is off, it still takes about $40\mu s$ to neutralize the beam and so the first $40\mu s$ the beam will have poor transverse emittance. A magnetic chopper can be ideal because it does not have the de-neutralization effect because the force on the Xe ions is small. (The force on the Xe ions is small since the speed of the Xe ions is small and so $\vec{v} \times \vec{B} \ll 1$). However, the PFN (pulse forming network) cannot recharge within ~$100\mu s$ after it discharges and so it is not possible to use a magnetic kicker with the existing PFN. The solution is to create a combination electrostatic and magnetic chopper (EMC) which is able to overcome all the disadvantages of the electrostatic and magnetic choppers and the de-neutralization problem of the electrostatic chopper.

The EMC works as follows (See Figure 4.4):

1. The magnetic kicker bends the first ~$40\mu s$ of the H- beam to the beam stop. The first $40\mu s$ of the beam from the source is discarded because it has not been neutralized yet.

2. The magnetic dipole is turned off by firing the thyratron and the H- beam goes straight through into the RFQ. Both the electrostatic and magnetic kickers remain off for $80\mu s$ which is the required bunch length for normal operations.

3. The electrostatic kicker is turned on by firing its thyratron which deflects the beam into the beam stop. The rise time of the kicker is about $40 \, \text{ns} \ll 1 \, \mu s$ and so there is no de-neutralization.

4. The H- source turns off, the capacitors of the PFN which power the EMC charge back up again and the EMC is ready to chop the beam again in $1/15 \, [\text{Hz}] = 67 \, \text{ms}$.
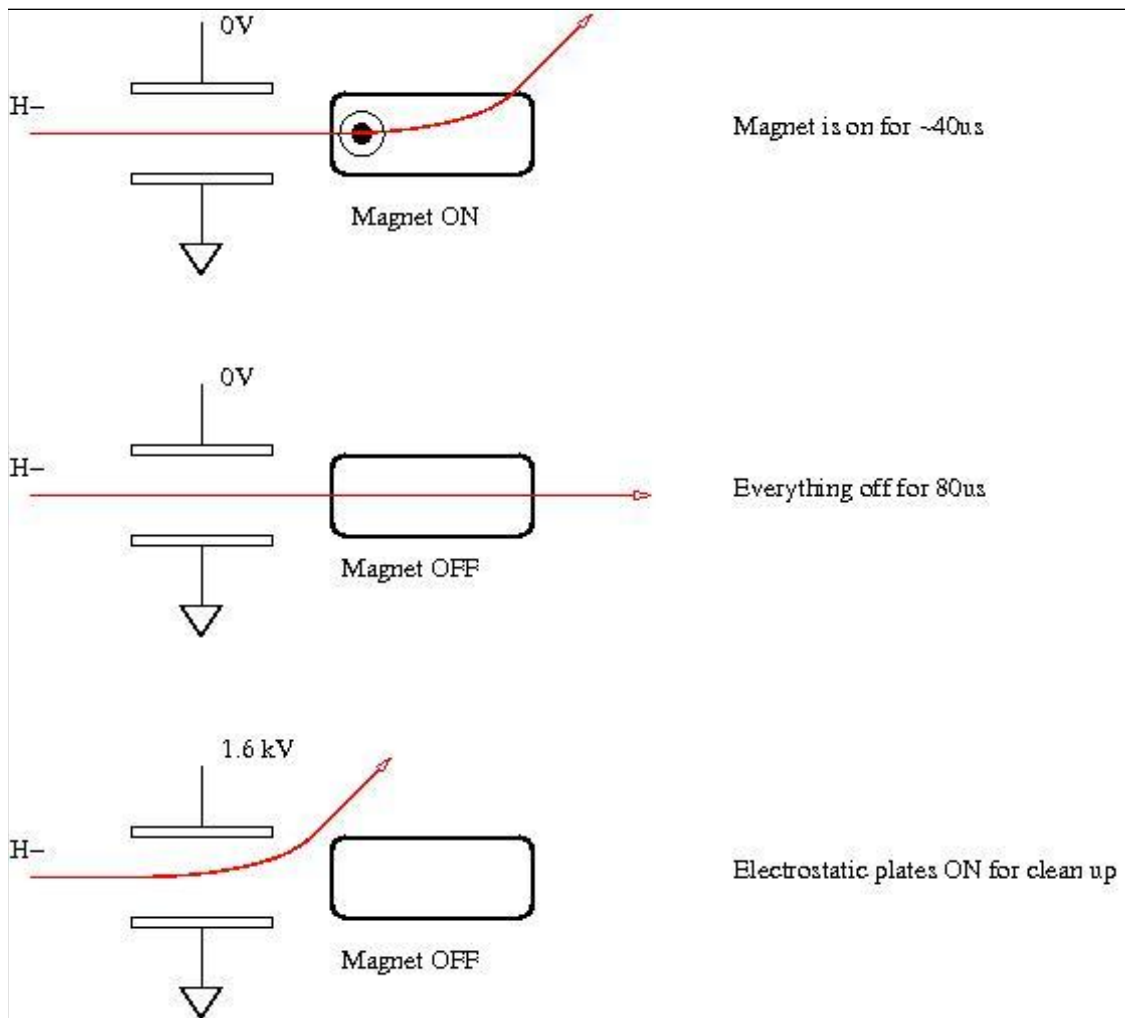
Figure 4: *The chopper is a combination of a electrostatic kicker and a magnetic kicker. The H- source is pulsed and the first 40μs of the H- beam is discarded because neutralization has not taken place yet. Everything is off for the next 80μs so that the beam is sent into the RFQ. After 80μs the beam is kicked by the electrostatic kicker into the beam stop. The cycle repeats after 1/15[Hz]=67ms when the PFNs have recharged and the H- source is pulsed again.*

4.2.3.a. The EMC Electrostatic Kicker Parameters

For the electrostatic kicker, the angular deflection per volt on 35 keV H- ions (which has momentum $p = 8.1 \times 10^6$ eV/c and β=0.00864) for plates which are separated by $d = 8$ cm (~3") and $l = 30$ cm (1 ft) long can be calculated with the formula

$$\theta_E = \frac{V_E l / \beta}{p d} \quad \Rightarrow \quad \theta_E / V_E = \frac{30/0.00864}{8.1 \times 10^6 \times 8} = 53.6 \ \mu rad/V \tag{4}$$

Therefore, if the centre of the chopper is about 60 cm (2 ft) from the entrance of the RFQ, the minimum voltage required to deflect the beam by $4.0 \cdot 0.9 / 60 = 0.083$ rad from the lower plate to

10

upper edge of the 1.8 cm entrance diameter aperture of the RFQ is 1.6 kV. This is not an unreasonable number and can be compared to the voltage on the BNL LEBT chopper which is 1.5 kV) [5] and the SNS LEBT chopper (4 – 5 kV for 65 keV H- beam) [10].

The electrostatic chopper can be designed to match the speed of the H- ions to the rise/fall time of the chopper voltage. If the rise/fall time of the chopper voltage is about 40 ns, then at 35 keV (β=0.00864) the H- ion travels a distance of about 10 cm during this time. Therefore, the chopper can be divided into strips which are about 10 cm in length to match the speed of the H-ions. This type of "slow wave" structure has been described in Ref. [5].

4.2.3.b. The EMC Magnetic Kicker Parameters

For the magnetic kicker, it is envisioned that it will have a ferrite yoke. And because of the fast fall time required < 40 ns, it is necessary to have a ceramic beam pipe. If the beam pipe is 3" in diameter, the magnetic gap can be chosen to be $h = 9$ cm (~3.5") and the magnetic length is $l = 30$ cm (1 ft), then the angular deflection is given by

$$\theta_M = \frac{B\,l\,[\text{T-m}]}{p[\text{eV/c}]/c[\text{m/s}]} = \frac{B \times 0.3}{\left[8.1 \times 10^6\right]/\left[3 \times 10^8\right]} = 11.1\,B\,[\text{rad}] \tag{5}$$

If the center of the kicker is about 30 cm (1 ft) away from the entrance of the RFQ, the angle required to deflect the beam from the lower edge of the beam pipe to the upper edge of the entrance hole of the RFQ is $\theta_M = \left[4.0 - 0.9\right]/30 = 0.16$ rad. Therefore, the required magnetic field is $B = 0.014$ T. The current required to produce this field for a window frame type dipole is given by

$$n\,I_M = B\,h/\left[2\,\mu_0\right] \Rightarrow n\,I_M = \frac{0.014 \times \left[9 \times 10^{-2}\right]}{2 \times \left[4\,\pi \times 10^{-7}\right]} = 500\,\text{A} \tag{6}$$

where n is the number of windings, I_M the current in the windings and $\mu_0 = 4\,\pi \times 10^{-7}\,\text{H/m}$ is the permeability of free space. If $n = 20$, then $I = 25$ A and for a $Z_M = 6.25\Omega$ system (Tevatron kicker magnet impedance), the peak power is $P_M = I_M^2\,Z_M = 25^2 \times 6.25 = 4\text{kW}$.

4.3. The RFQ

The BNL RFQ model [11] was optimized with PARI to produce the RFQ model which is used in all the simulations of this report. PARI was set up to optimize the output energy to 753 keV and to adjust the RFQ vane modulation only. The result is an RFQ with parameters summarized in Table 4.2. Some of these parameters are of plotted in Figure 4.5. Using these parameters, a PARMTEQM simulation was set up to transport 10^4 particles from the entrance to the exit of the RFQ. For 50mA of H-, only 2% of the H- ions are lost in the simulation. Figure 4.6 shows the result of the transport through the RFQ and Figures 4.7, 4.8 and 4.9 show the phase space and real space distributions of the particles before and after they have gone through the RFQ. The initial phase space distributions used in the simulation are from BNL (See the matching results at the entrance of the RFQ using Trace2D which is shown in Figure 4.3) because the FNAL RFQ will be very similar to the BNL RFQ.

Parameter	Value	Units

Parameter	Value	Units
Input energy	35	keV
Output energy	753	keV
Frequency	201.25	MHz
Number of cells	147	
Length	162.95	cm
Minimum radial aperture	0.26	cm
Maximum peak surface field	21.45	MV/m
Peak cavity power[2]	~100	kW
Duty factor (80 μs, 15 Hz)	0.12	%
Design current	50	mA
Modulation m	$1 \leq m \leq 2.1$	
Intervane voltage	66.87	kV
Transmission efficiency	98	%
Input emittance (x,y)(norm, $1\times$ rms)	0.3	$\square \cdot$ mm$\cdot$ mrad
Output emittance (x,y) (norm, $1\times$ rms)	0.3	$\square \cdot$ mm$\cdot$ mrad

Table 2 *The parameters of the RFQ model which has been optimized from the BNL model.*
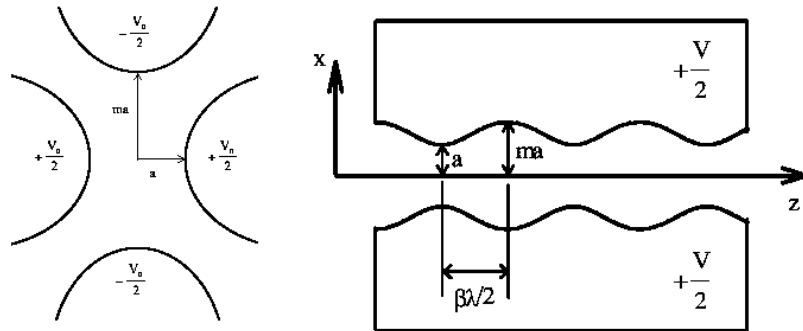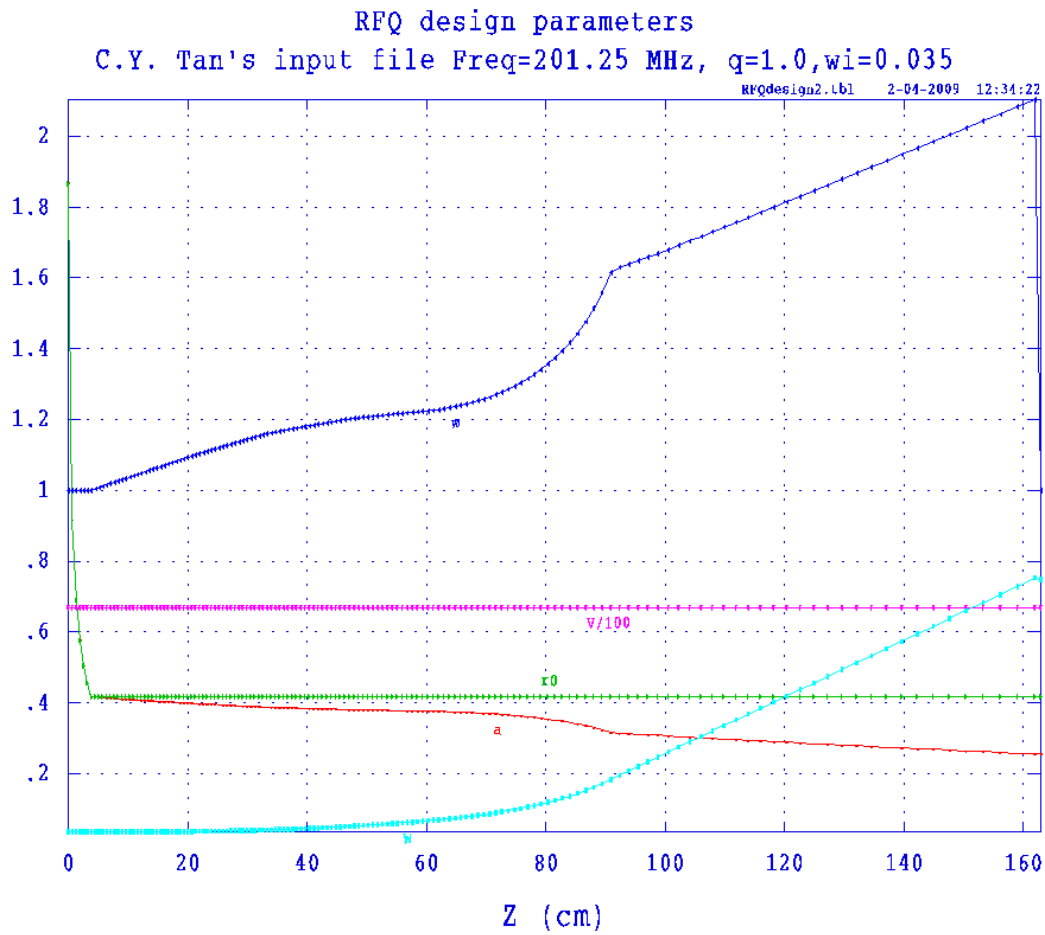
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2   BNL RFQ power requirement.

Figure 5: *This is a plot of some of the RFQ parameters versus the length of the RFQ. a (cm, red) is the radius of the aperture, m (blue) is the modulation index, W (MeV, cyan) is the energy of the beam, $V/100$ (kV, magenta) voltage on the vanes divided by 100, and r_0 (cm, green) is the mid cell radial aperture. (Note: Bottom figure are Figures III-3 and III-4 of the PARMTEQM manual [14].)*
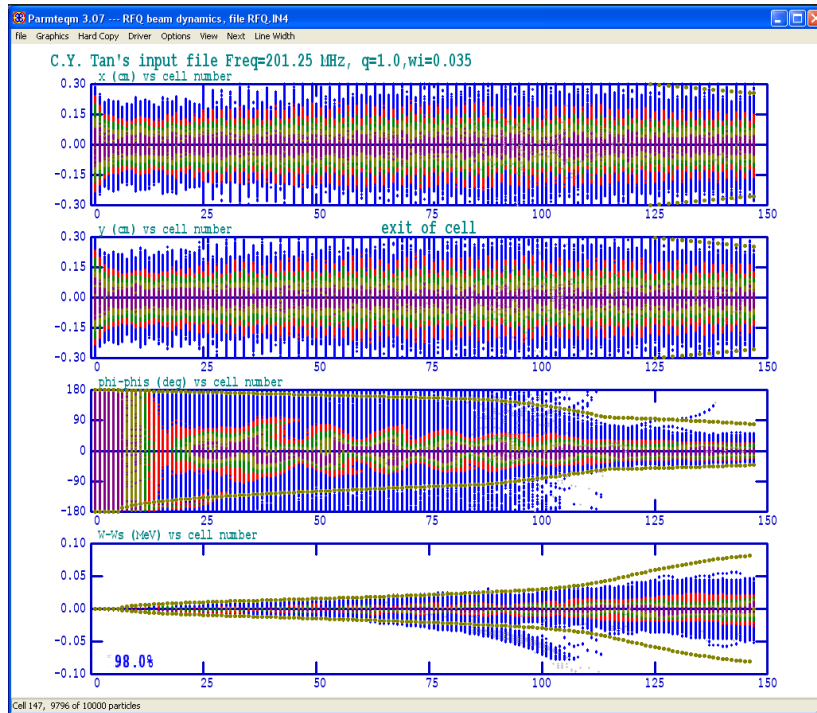
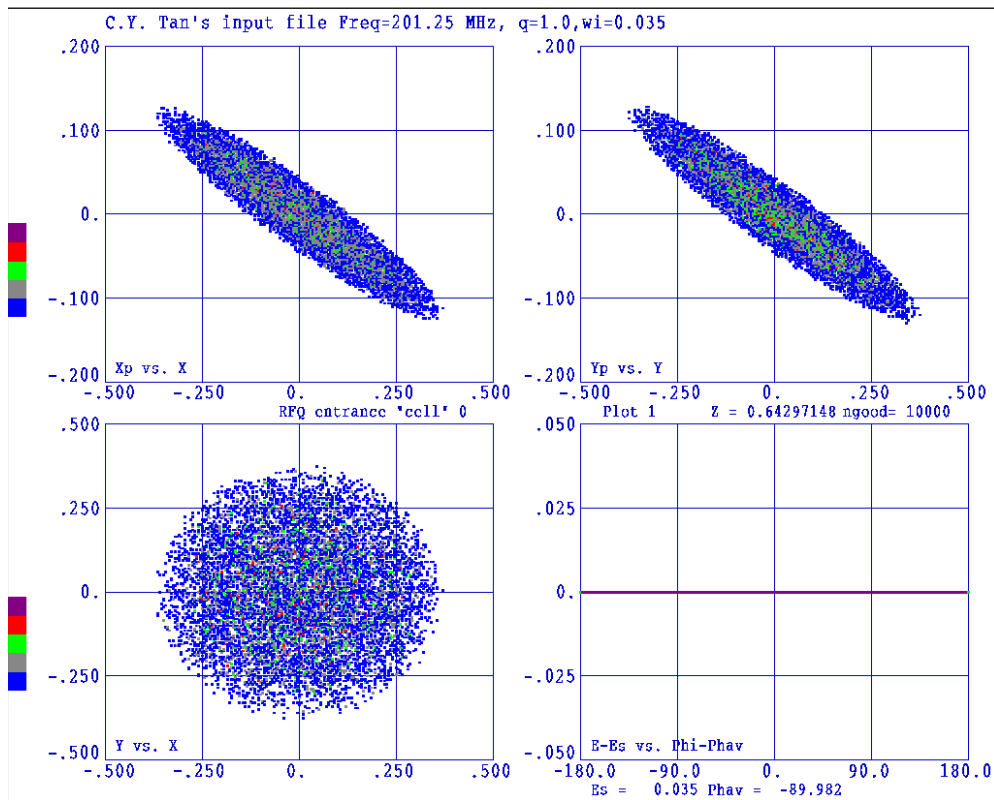**Figure 7**: This is a PARMTEQM simulation of 50mA beam going through the RFQ. The transmission efficiency is 98%.

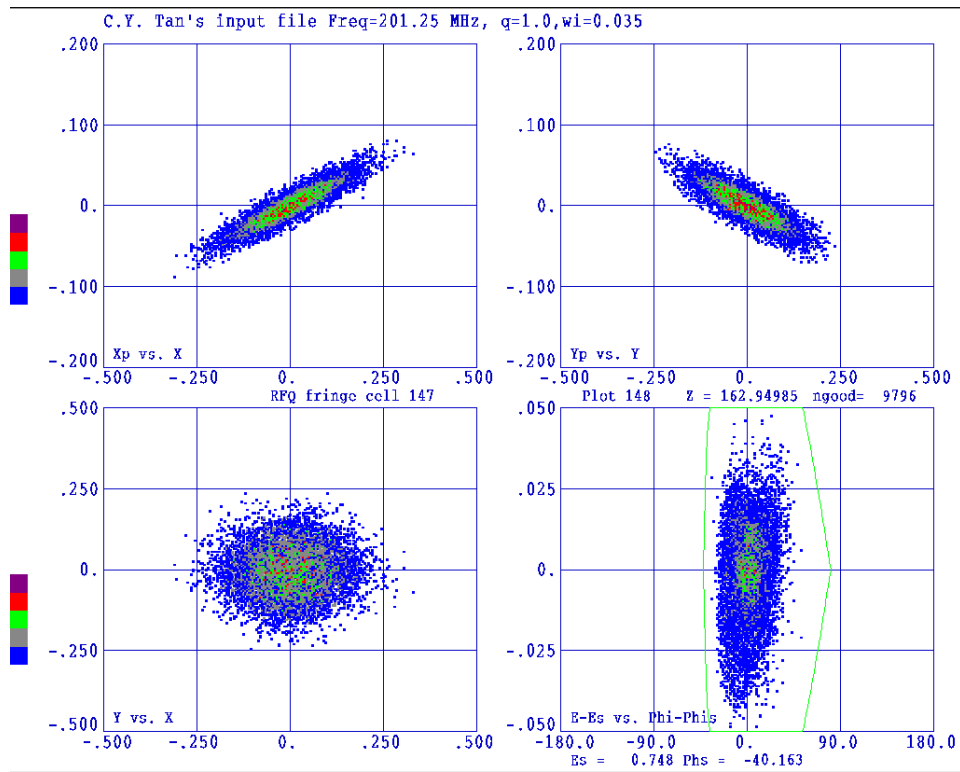**Figure 6**: The initial phase space distribution at the

Figure 9: *The phase space distribution at the end of the*
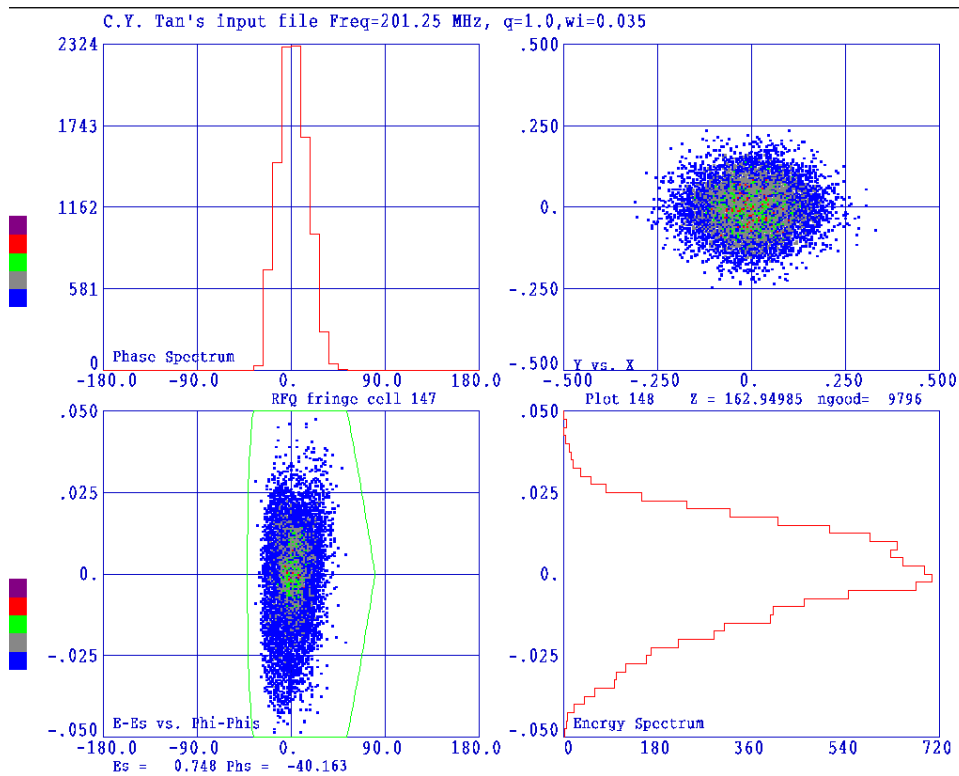

Figure 8: *The longitudinal distribution at the end of the RFQ.*

4.4. Optics for the MEBT

The plan is to use the present BNL MEBT for the proposed MEBT. The MEBT contains 1 buncher and 3 quadrupoles for matching, 2 sets of steerers in both planes, 1 current transformer and 1 Faraday cup for diagnostics and a beam stop for safety. BNL has managed to squeeze all these parts into 73.25 cm of space. See Figure 4.10. The MEBT lattice which matches to the present DTL calculated using Trace3D is shown in Figure 4.11. Note: $\square\square= 60\,mm$ for the MEBT and so it is unrealistic to design the lattice with $\beta\lambda$ spacing because it is too short.
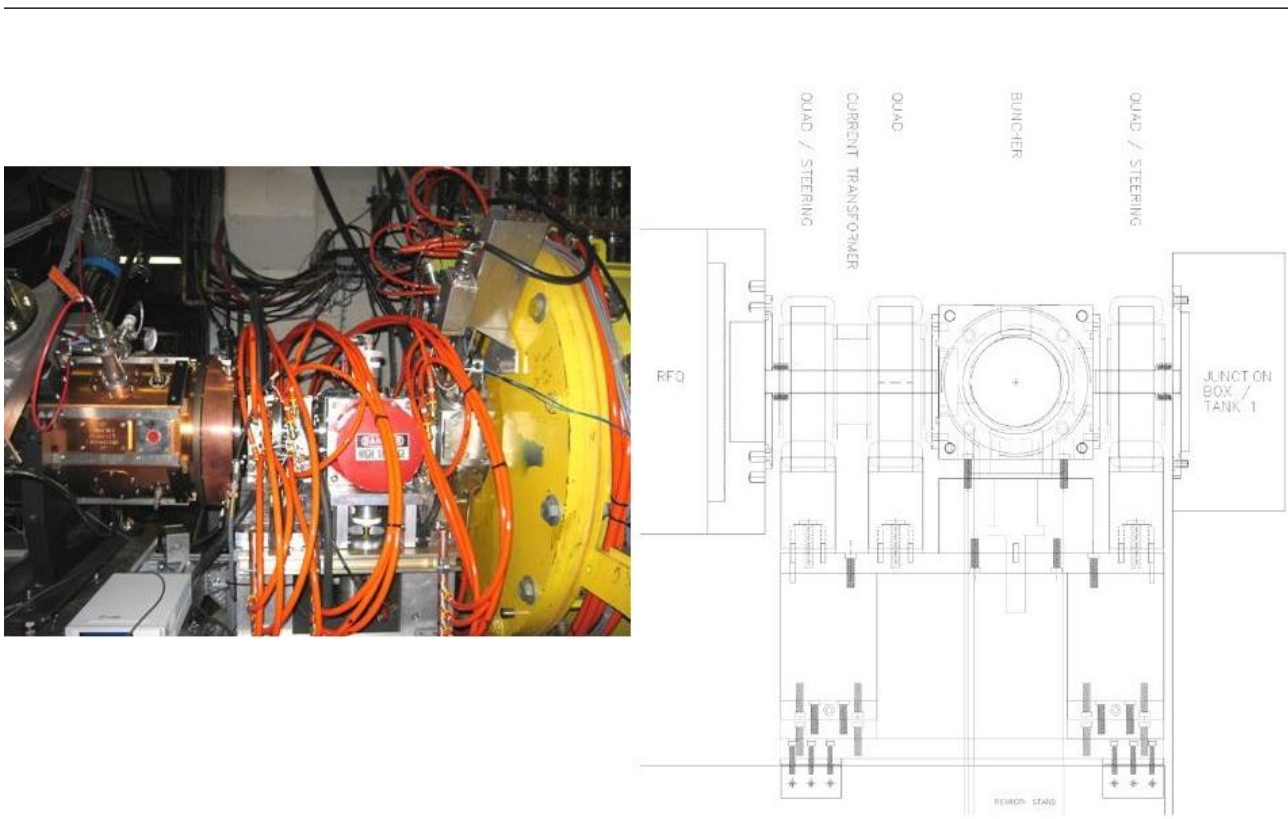

Figure 10: *This is the BNL MEBT which only occupies 73.25 cm of space between the end of the RFQ and the start of the first DTL.(Picture courtesy of D. Raparia)*

Trace3D Element ID	Element Type	Value	Comments
11	Quad	-43.5 T/m	Within specs of BNL style quads used in their MEBT.
13	Quad	31.3 T/m	

Trace3D Element ID	Element Type	Value	Comments
19	Quad	-16.1 T/m	
15,17	Buncher	34.5 kV	Value is E_0TL. Buncher has two gaps.

Table 3 *Summary of the relevant parameters used to match the H- ion beam from the end of the RFQ to the entrance of the DTL. See Figure 4.11 for the Trace3D element ID.*
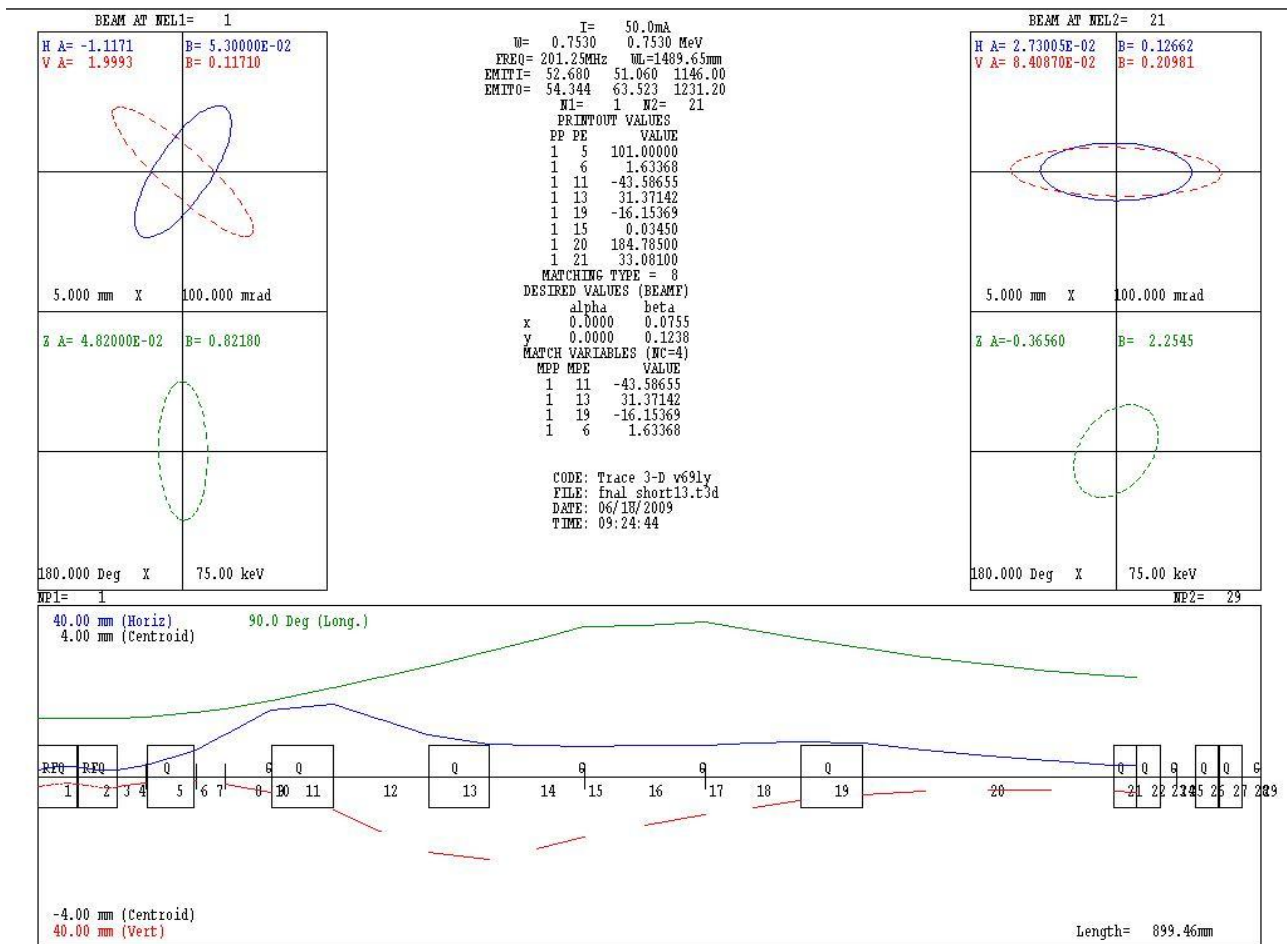

Figure 11: *The H- beam is transported from the end of the RFQ to the start of the DTL using the same BNL MEBT optics. PARMILA shows that at 50mA, (80.3 ± 0.4)% of the beam is captured and transported to the end of the DTL.*

4.4.1. Buncher

The effective buncher gap voltage calculated by Trace3D is $E_0TL = 34.5\,\text{kV}$. The peak

voltage V_g across the gap of the buncher can be calculated by first calculating the peak E-field E_0 from the following formula

$$E_0 = \frac{E_0 TL}{T \times L} \tag{7}$$

where L is the length of the RF gap and T the transit time factor (dimensionless). T is approximately given by the following

$$T = \frac{\sin\left[\frac{\omega_{RF}}{c}\frac{L}{2}\right]}{\frac{\omega_{RF}}{c}\frac{L}{2}} \tag{8}$$

where $\omega_{RF} = 2\pi \times f_{RF}$, and c is the speed of light. And so for an RF gap of $L = 1"$ and 750 keV H-ions ($\beta = 0.04$), the transit time factor is calculated to be $T = 0.73$. Substituting these values into Eq. (7), $E_0 = 1.8$ MV/m and thus the peak gap voltage $V_g = E_0 L = 47$ kV.

Parameter	Value	Units	Comments
Energy gain per unit charge $E_0 TL$	34.5	kV	Calculated by Trace3D. See Figure 4.11.
Gap length L	1	inch	Assumption
Gap voltage V_g	47	kV	
Shunt impedance R_s	1	MΩ	Assumption
Transit time factor T	0.73		
Total power $P_T/0.5$	6	kW	Worst case for 1 gap and 50% thyratron efficiency.

Table 4 *Single gap buncher parameters using E_0TL = 34.5 kV. For a double gap buncher, see text, Table 4.3 and Figure 4.11.*

With this gap voltage it is possible to calculate the power requirements of the buncher if the shunt impedance R_s is first selected. A reasonable value for a copper cavity is $R_s = 1$ MΩ and from the definition of shunt impedance, the average power loss from dissipation on the walls of the cavity P_D is [12] (Note: this definition takes into account the transit time factor T)

$$P_D = \left(E_0 TL\right)^2 / R_s = \left(34.5\,10^3\,[\mathrm{V}]\right)^2 / 10^6\,[\Omega] = 1.2\,\mathrm{kW} \tag{9}$$

The power transferred to the beam by a buncher in the ideal case is zero because the earlier half of the beam is decelerated while the latter half is accelerated equally and thus the total energy delivered is zero. However, in the worst case scenario, all the beam is accelerated and so the power P_b delivered to the beam is

$$P_b = I_{\text{beam}} \times E_0 TL = \square 50 \times 10^{-3}[\text{A}]\square \times \square 34.5 \times 10^3[\text{V}]\square = 1.7\,\text{kW} \tag{10}$$

Therefore, the total power P_T required for the buncher is the sum of power loss from dissipation and the power delivered to the beam [13]

$$P_T = P_D \square P_b = \square 1.2 \square 1.7 \square \text{kW} = 3.0\,\text{kW} \tag{11}$$

If the buncher has two gaps, R_s can be increased to $2 \times R_s$ so that P_D remains unchanged but $P_b \square 2 \times P_b = 3.4\,\text{kW}$ and so $P_T = 4.6\,\text{kW}$ for two gaps.

Needs correction: It should be noticed that P_T does not take into account the efficiency of the RF generator which is typically between 40% to 60%. Assuming the efficiency to be 50%, the RF generator must provide at least $P_T/0.5 = 6$ kW of power. Since the buncher has two gaps in the design, the required thyratron power is 12 kW. The buncher parameters are summarized in Table 4.4. Notice that one IPA RCA 7651 thyratron can provide up to 8kW of power and therefore two 7651's are needed for the buncher. Note: this is an over estimation.
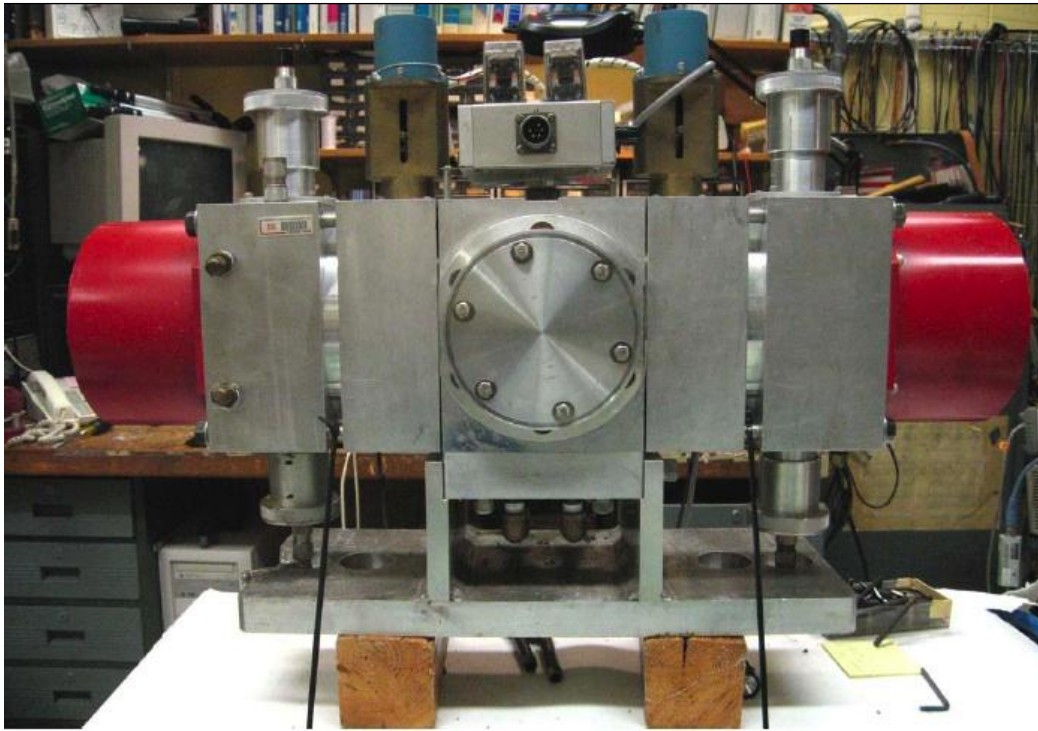

Figure 12: *This is a picture of the modified two gap buncher used in the BNL MEBT. (Courtesy of D. Raparia)*

4.5. Layout

The present layout of the H- and I- lines are shown in Figure 4.13. All the elements in the I-line upstream of the DTL will be removed for the installation of the proposed injector. The approximate space required for the proposed injector is drawn in shades of red on the floor plan of the pre-accelerator enclosures shown in Figure 4.14. It is clear from this figure that the proposed injector will occupy a lot less space than the existing injector.
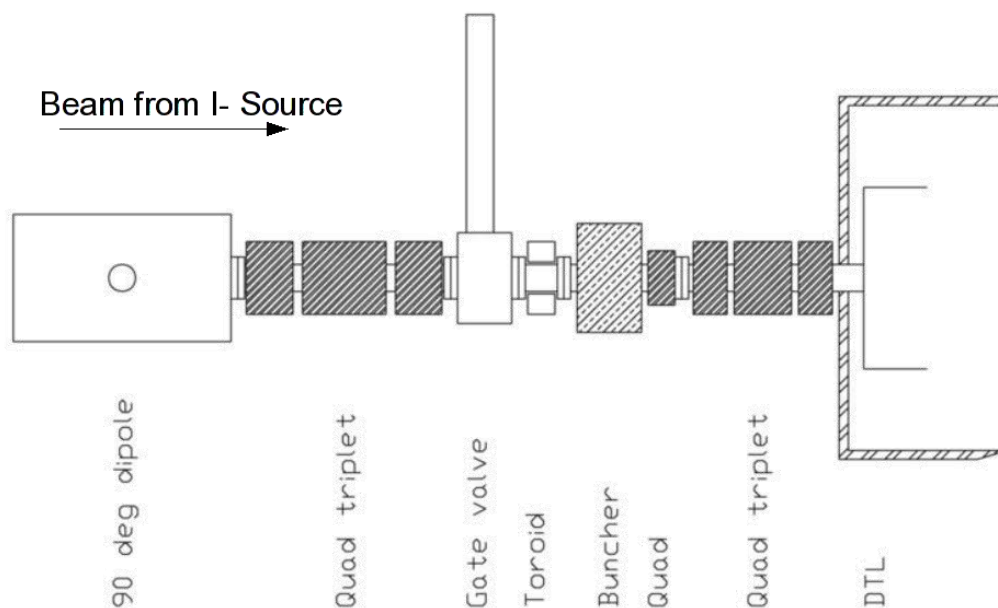
Figure 13: The photograph (composited from three photographs) in this figure shows the present I- and H- transport lines. The drawing below it shows the elements in the I- line. All the elements upstream of the DTL will be removed for the new injector installation.
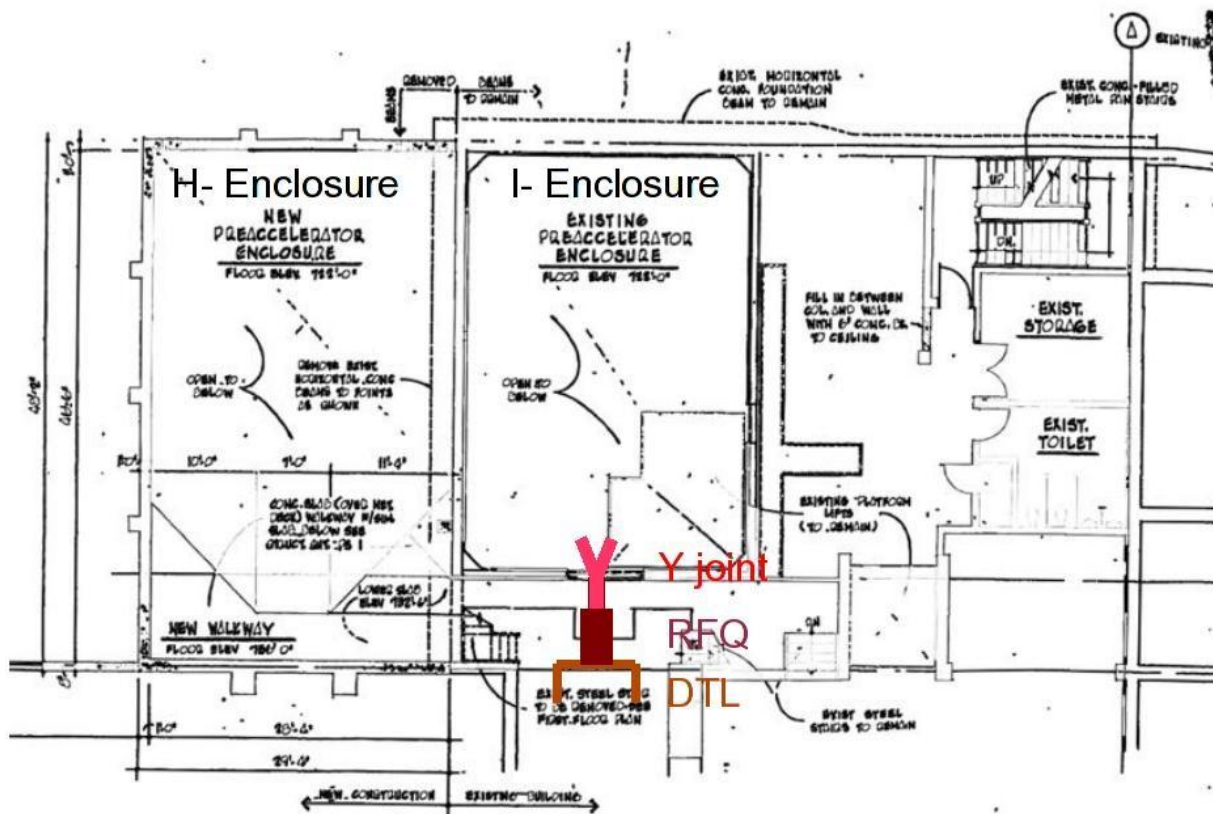
Figure 14: *The floor plan of the existing pre-accelerator enclosures which house both the H- and I- sources. A sketch of the new injector is drawn in shades of red in this figure. It is clear that the proposed injector will occupy a lot less space than the present I- injector.*

5. Performance Goals

The goal is to have an injector that performs as well as the present Cockcroft-Walton system. This means that

1. the reliability and uptime of the proposed injector must be at least 97%. Reference ?

2. the beam current at the end of the DTL 1 must be at least 37.5 mA. See Figure 5.1.

Table 5.2 shows the minimum beam current requirements at each stage of the proposed injector which will give the same beam current at the end of DTL 1 with the Cockcroft-Walton.
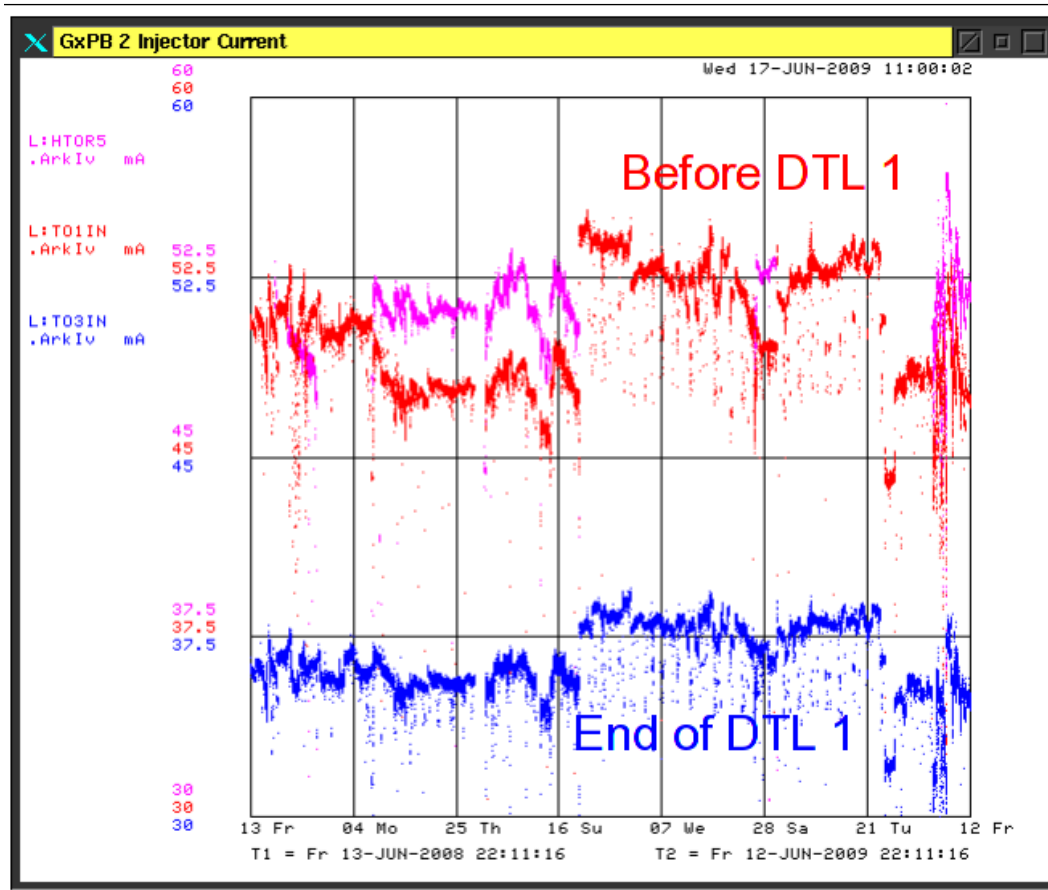
Figure 15: *This figure shows the performance of the present injector for the past year. Maximum current at the end of the first DTL is about 37.5mA. The loss of H- by going through the DTL is about 30% because the beam in the LEBT is essentially DC and the tails are not captured in the DTL.*

Location	ϵ_x (norm., 1σ, $\Box\cdot$ mm$\cdot$mrad$)$	ϵ_y (norm., 1σ, $\Box\cdot$ mm$\cdot$mrad$)$	ϵ_z (norm, 1σ, $\Box\cdot$ mm$\cdot$mrad$)$	Comments
Start of DTL 1	0.86	0.91	?	When?

Table 5 *These are the present transverse and longitudinal emittances at the start of DTL 1 which the proposed injector must reproduce or improve upon.*

Location	Current* (mA)	% Transmission from previous location	Comments
Output of H- source	60		Source can operate up to 100mA. See ref. [2].
End of LEBT before	50	84	See section **Error!**

Location	Current* (mA)	% Transmission from previous location	Comments
RFQ			**Reference source not found.**
End of RFQ	49	98	See section **Error! Reference source not found.**
End of DTL 1	39.5	80	See section **Error! Reference source not found.**

Table 6 *These are minimum beam current requirements for the proposed H-injector which matches the present slit source+Cockcroft-Walton injector.*The definition of beam current is discussed in this section (Section **Error! Reference source not found.**).*

At the output of the H- source, the beam current I_s is defined to be

$$I_s = Q_s / T_s \tag{12}$$

where Q_s is the total charge at the output of the H- source and $T_s \approx 80\,\square\mathrm{s}$ is the length of the pulse.

In the simulations which use either PARMTEQM [14] or PARMILA [15], the beam current I_beam is defined to be

$$I_\text{beam} = qNf_\text{bunch} \tag{13}$$

where q is the charge per particle, N is the number of H- ions, f_bunch is the bunch frequency. In the simulations, it is assumed that $f_\text{bunch} = f_\text{RF} = 201.25\,\mathrm{MHz}$ because all the adjacent buckets are filled in the ~80μs macro pulse. This means that $I_s = I_\text{beam}$ if there are no losses because a uniformly distributed Q_s decreases linearly as the size of the macro pulse is linearly shrunk from T_s to $1/f_\text{RF}$.

6. Cost Estimate

Bill?

7. Conclusion

8. Acknowledgments

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1. The BNL linac group: J. Alessi, D. Raparia and V. Lodestro who graciously hosted three of the authors (Bollinger, Schmidt and Tan) in the fall of 2008 for a tour of the BNL injector and who gave them much of the information used in this proposal.

2. D. Raparia (BNL) who generously supplied the BNL LEBT and MEBT design which served as the base line design in this proposal.

3. M. Popovic (FNAL) who supplied the present DTL PARMILA model used in the simulations.

A.1. The BNL Injector

The BNL injector will be discussed in the following two subsections. The reason for this discussion is because the BNL injector was upgraded from a nearly identical FNAL style slit source+Cockcroft-Walton in the fall of 1988 to a round source+RFQ. The motivation for doing the replacement at BNL came from the expectation of "improved reliability, simpler maintenance, and the added convenience of having the ion source located at nearly ground potential" [16]. This is *exactly* the same argument that will be used in this proposal.

The round source+RFQ which has been operational at BNL since then, has operational parameters which are nearly identical to the FNAL requirements and so a direct comparison between the two can be made. The operational experience of the BNL round source+RFQ has been very positive and thus an upgrade of the FNAL injector to this configuration should carry very little technical risk.

A.1.1. The BNL Injector (1982-1989)

The BNL injector switched to H- operation in 1982 [2]. The 750 keV injector is nearly identical to the present FNAL 750 keV injector except that it has only one slit source+Cockcroft-Walton while FNAL has two slit source+Cockcroft-Waltons. The injector typically runs at a repetition rate of 6.6-7.5 Hz with a pulse width of about 500μs. The current at the output of the Cockcroft-Walton is about 40-50 mA [17]. The beam is then accelerated and either injected into the Booster or switched into a second beam line for isotope production.

A.1.2. The BNL Injector (1989-present)

BNL built a round source+RFQ injector which replaced the one slit source+Cockcroft-Walton in 1989. The typical running parameters of the round source are shown in Table 1.1. This can be compared to the typical running parameters of the slit source shown in Table ?? and it is clear that the FNAL source is operating at about 40% lower power than the BNL source. Even when operating at this power, the single BNL H- source has been "very reliable, operating continuously for ~6 months, with essentially no parameter adjustments required once the source is stabilized." [2].

There has been a number of reconfigurations of the LEBT and MEBT at BNL. The present configuration [4] is shown in Figure 1.1. The length of the LEBT for the unpolarized, high intensity H- source is about 4m because it is constrained by the position of the polarized H- source. In order to get maximum transmission of the H- beam from the source to the RFQ, Xe gas focusing must be employed. There is a 30% improvement of the transmission of H- beam in the LEBT with Xe gas focusing compared to without gas focusing. However, gas focusing does strip the H- beam and causes a loss of 32% of the beam in the LEBT (gas stripping will be discussed in section **Error! Reference source not found.**).

The LEBT transports the H- beam to the RFQ. The RFQ is about 1.5m long and accelerates the 35 keV beam from the source to 750 keV. The RFQ has not had any problems since its installation [18].

The 750 keV beam is transported to the DTL by the MEBT. The length of the MEBT has been shortened by 70 cm from the previous configuration of about 7 m. The new MEBT has greatly improved the losses (essentially zero), transmission and emittance of the beam at the end of the DTL. The improvements are about a factor of 2 smaller in emittance in both planes compared to the previous configuration and a transmission efficiency of between 65 – 70% compared to the previous configuration of 50 – 55% [4].
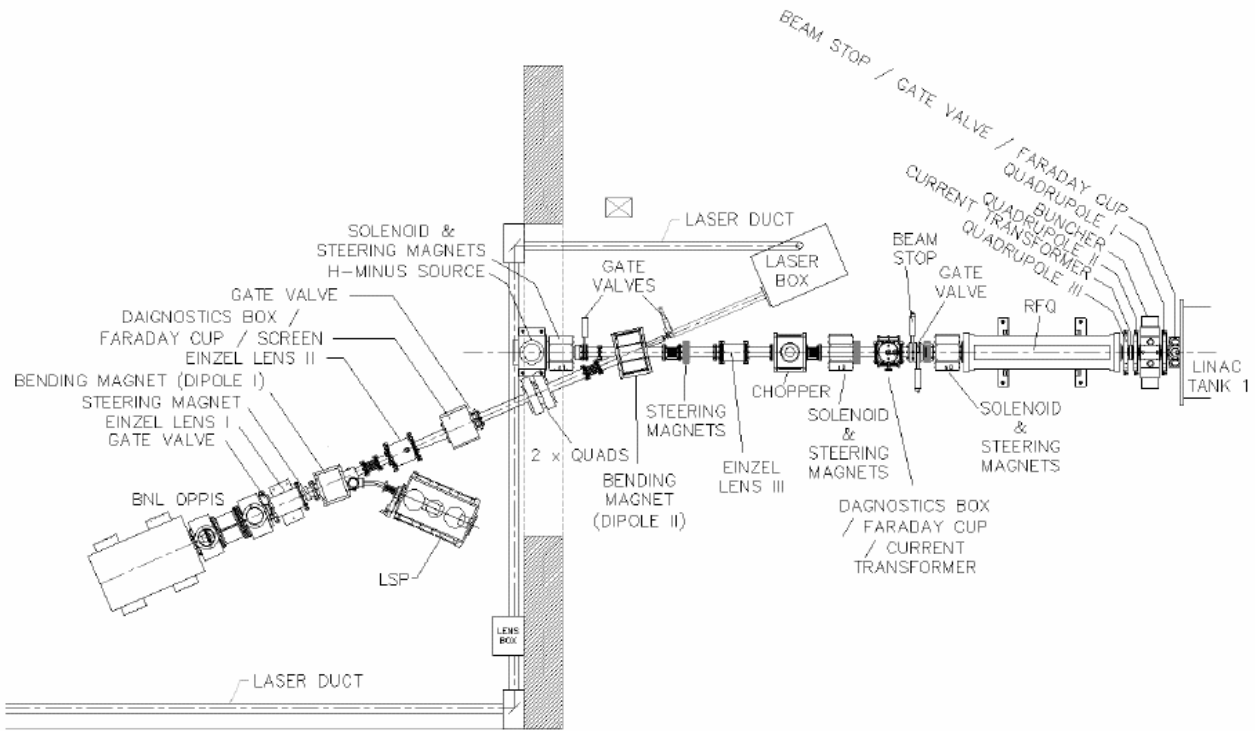
Figure 16: *This is the BNL injector (as of 2009 [4])which has a H- magnetron source and a polarized H- source. The MEBT, which is after the RFQ and before Linac Tank 1 is only 73.25 cm long, contains 1 buncher, 3 quadrupoles, 2 sets of horizontal and vertical steerers (not shown in drawing), 1 current transformer and 1 beam stop/gate valve/Faraday cup package. Figure 4.10 is a picture of the MEBT.(Picture courtesy of D. Raparia)*

Parameter	Value	Units
H- current	90 – 100	mA
Current density	1.5	A/cm^2
Extraction Voltage	35	kV
Arc Voltage	140 – 160	V
Arc current	8 – 18	A
Repetition Rate	7.5	Hz
Pulse Width	700	μs
Duty factor	0.5	%

Parameter	Value	Units
rms Emittance	~0.4	⬚· mm· mrad
Cs consumption	< 0.5	mg/hr
Gas flow	~2	sccm
Average Power	$150\,V \times 150\,A \times 5\,Hz \times 600\,⬚s = 68$	W

Table 7 *Some BNL H- round source parameters copied from Ref. [2]. (Courtesy of J. Alessi).*

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